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MSX Satellite: Flight Measurements of Contaminant Films*

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Abstract

The Midcourse Space Experiment (MSX) satellite was launched on April 24, 1996. Earlier, descriptions of the Ballistic Missile Defense Organization (BMDO) satellite and some of the early results were presented. This paper provides an update of the data accumulated through the end of the cryo period. The cryo period included the time from launch through the lifetime of the SPIRIT 3 cryogenic telescope. This period covered about 10 months and ended when the dewar containing solid hydrogen warmed up to a temperature above 12 K. The five QCMs onboard the satellite provided data that have been invaluable in characterizing contamination levels around the spacecraft and inside the SPIRIT 3 cryogenic telescope. One of the QCMs, the CQCM, was located internal to the SPIRIT 3 cryogenic telescope and was mounted adjacent to the primary mirror. Real-time monitoring of contaminant mass deposition on the primary mirror was provided by the CQCM, which was cooled to the same temperature as the mirror — ~20 K. Thermogravimetric analyses (TGAs) on the CQCM provided insight into the amount and species of contaminants condensed on the SPIRIT 3 primary mirror. The four TQCMs were mounted on the outside of the spacecraft for monitoring contaminant deposition on the external surfaces. The TQCMs operated at ~ –50°C and were positioned strategically to monitor the silicone and organic contaminant flux arriving at specific locations. These TQCMs were located near the UV instruments or positioned to monitor mass coming from specific contaminant sources such as the solar panels. Updated time histories of contaminant thickness deposition for each of the QCMs are presented. Changes in contaminant deposition were seen during the SPIRIT 3 end of cryo warm-up, and implications will be discussed.

Introduction

This paper presents an up-to-date summary (as of August 23, 1997) of the Midcourse Space Experiment (MSX) (Fig. 1) satellite flight data that have been recorded from the quartz crystal microbalances (QCMs) since its launch. Onboard the satellite were five QCM mass deposition instruments. Four of these were temperature-controlled QCMs (TQCMs) for monitoring contaminant mass deposition on the outer surfaces of the spacecraft.

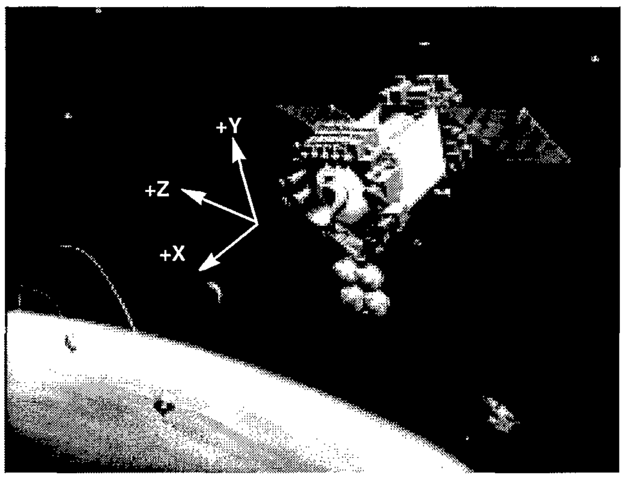

Fig. 1. Artist's drawing of Midcourse Space Experiment in orbit and showing reference axes.

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The fifth was a cryogenic QCM (CQCM) which was located adjacent to the primary mirror of the SPIRIT 3 cryogenic telescope.

The SPIRIT 3 infrared telescope (Fig. 2) was the primary MSX instrument, and had sensor system components cooled to temperatures varying between 8.5 K and 65 K. The operational lifetime of SPIRIT 3 on orbit was approximately 10 months, so a small arrival rate of condensable gases could have led to a measurable degradation of its optical performance. Located adjacent to the primary mirror and operating at the same temperature (~20 K) was the cryogenic quartz crystal microbalance (CQCM) which measured the condensed contaminant mass throughout the lifetime of the SPIRIT 3 sensor. The CQCM, being at the same temperature as the primary mirror, was assumed to condense arriving gases at the same rate as the mirror. By knowing the condensed mass, the contaminant film thickness was calculated. Even prior to launch, the CQCM was extremely useful for monitoring contaminant deposition on the primary mirror during preflight ground testing operations and calibrations of SPIRIT 3. The CQCM was used to help identify the species of the contaminants condensed through thermogravimetric analysis (TGA) techniques. In the CQCM TGA mode, the sensing surface was allowed to warm up at a controlled rate and the evaporated mass was measured as a function of temperature. By monitoring the temperatures at which the various gases evaporated (which depended on their vapor pressure), the gas species were identified and their approximate thicknesses determined.

Contaminant deposition can affect optical element performance by: (1) changing the reflectance /transmittance, and (2) increasing scatter of the optical element. The changes in bi-directional reflectance distribution function (BRDF) of the SPIRIT 3 primary mirror surface due to these deposited species and film thickness were also compared to laboratory results for films of the same species and thicknesses.[1,2] In the infrared region, the effects of condensed films on sensor surfaces can be particularly detrimental because of the films' selective wavelength absorption. Once the contaminant thickness and species had been determined from the CQCM data, this information was used to calculate the changes in mirror reflectance using pre-existing optical property data (refractive and absorptive indices) of the films.[3]

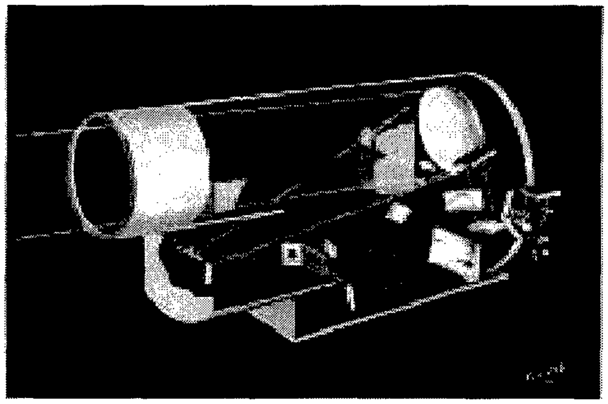

Fig. 2. Artist's drawing of SPIRIT III Telescope Sensor System.

The four TQCMs were commanded to temperatures in the –40 to –50°C range to measure the contaminant deposition at locations external to the spacecraft near the other two primary instruments — the Space-Based Visible (SBV) telescope and the Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) instrument (Fig. 3). With the TQCMs operating at these relatively warm temperatures (compared with the CQCM), water vapor and low molecular weight gases will not condense at these temperatures under the vacuum conditions of space. The measured deposition was from

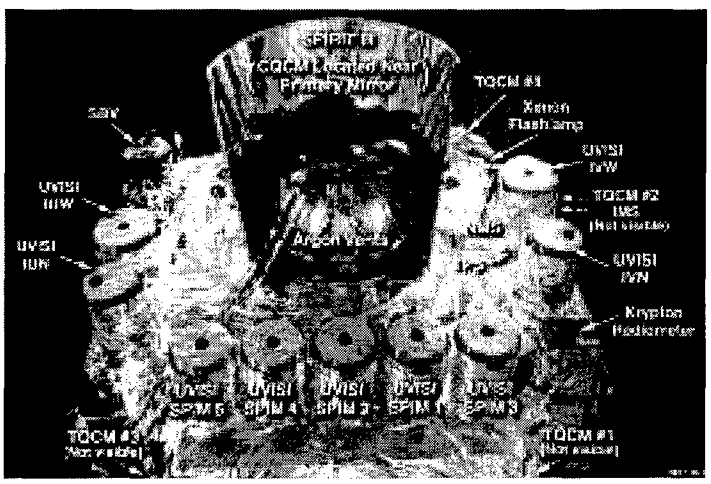

Fig. 3. Photograph of instrument section of MSX (+X direction).

heavy molecules (such as hydrocarbons and silicones) outgassed from some of the materials used in the spacecraft and its instruments. As expected, the TQCMs having view factors of the solar panels have shown the largest deposition rates. The TQCM looking in the same general direction as the science instruments (+X) also indicated significant contaminant levels. The TQCM located in the spacecraft wake position showed relatively little accumulation as expected.

The TQCMs and CQCM have remained operational well beyond the 10 months of cryogenic operation for the SPIRIT 3. Although the cryogenic portion of the experiment has been completed, the QCMs are continuing to provide valuable contamination data relating to space materials outgassing rates and the space aging processes.

Description of MSX Satellite Program

The Midcourse Space Experiment (MSX) satellite was launched into a 903-km, 99.4-deg orbit from Vandenberg Air Force Base on April 24, 1996 (Day 115). The MSX satellite (Fig. 4) was funded by the Ballistic Missile Defense Organization (BMDO). The MSX satellite was part of a demonstration/validation program which had both defense and civilian applications.[4] With telescopes and imagers operating in the wavelength range from the UV through the infrared spectrum, data from the spacecraft were used in the identification and tracking of ballistic missiles during midcourse flight. Data were also collected for test targets and space background phenomena. The satellite was also used to monitor in-flight contamination, and to investigate the composition and dynamics of the Earth's atmosphere. The UV-Visible data were collected by a suite of four imagers and five spectrographic imagers (UVISI) which were operating in wavelength segments from 110 - 900 nm. Visible and Near-IR data were collected by the Space-Based Visible (SBV) sensor system which was comprised of a CCD camera operating in the 400 to 1,000-nm wavelength range. Both of these sensor systems operated over the –20°C to +30°C temperature range. The final sensor system was the Spatial Infrared Imaging Telescope (SPIRIT 3), a cryogenic telescope that was cooled from an onboard dewar of solid hydrogen with component temperatures ranging from 8.5 K up to 65 K, depending on their location and spacecraft orientation. A gold-coated sun shield was placed near the entrance of SPIRIT 3 to protect against unwanted solar radiation getting into the telescope. It should be noted that all of the science instruments were located on the +X face of the spacecraft (see Fig. 3), with the electronics placed near the –X face at the other end of the spacecraft. This was designed to minimize contaminants outgassing from warm electronic boxes and condensing on science instrument surfaces. A contamination control plan was followed throughout the mission to minimize contamination levels on orbit. Based on results from all of the contamination instruments, this goal was achieved.

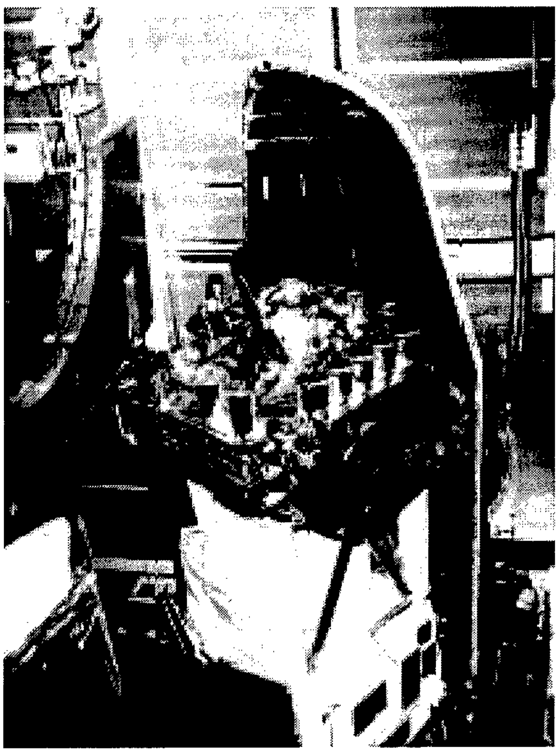

Fig. 4. Photograph of MSX Satellite partially covered with shroud just before launch.

The MSX organization was comprised of 8 scientific/technical teams for the functional areas of (1) Early Midcourse Targets, (2) Late Midcourse Targets, (3) Space Surveillance, (4) Earthlimb Backgrounds, (5) Shortwave Terrestrial Backgrounds, (6) Celestial Backgrounds, (7) Data Certification and Technology Transfer, and (8) Contamination. Each of these principal investigator teams was responsible for designing experiments, provid-

ing necessary flight instrumentation, and performing analysis of the ground calibration and flight data. The Contamination Experiment utilized the following instruments: (1) a total pressure sensor, (2) a neutral mass spectrometer, (3) an ion mass spectrometer, (4) krypton and xenon flashlamps for measuring water molecular density and particulates, respectively, and (5) four temperature-controlled QCMs (TQCMs) and one cryogenic QCM (CQCM) that was located inside the SPIRIT 3 cryogenic telescope. With these instruments it was possible to characterize the time-varying health of the spacecraft throughout its mission.

MSX stayed in its parked mode orientation for most of the time. In this mode, the –Y face of MSX (see axes locations in Fig. 1) was facing towards the sun for maximum power generation by the solar panels. The +Z face was into ram and the –X face was always facing Earth. The +X direction was always perpendicular to the sun vector and looking out and away from Earth to minimize thermal loading on the SPIRIT 3 telescope. Generally, the spacecraft remained in the parked mode prior to spacecraft maneuvers for dedicated experiments that required other orientations. Upon completion of the data collection event, the spacecraft was returned to the parked mode.

Quartz Crystal Microbalance Contamination Instrument Descriptions

Cryogenic quartz crystal microbalance

The CQCM is a Mark 16 model[5] from QCM Research of Laguna Beach, CA. The CQCM uses two quartz crystals (to minimize temperature effects) which oscillate at 10 MHz; they are positioned such that the sense crystal is exposed to the environment external to the sensor, whereas the reference crystal is protected from any deposition. The difference frequency is directly proportional to the mass condensed on the sense crystal. The CQCM on MSX is located adjacent to, and is thermally coupled to, the cryogenically cooled primary mirror of the SPIRIT III telescope. It was used to monitor deposition of contaminants on the interior optics and, with associated optical data, to determine the degradation in mirror performance. The CQCMs were calibrated and characterized at temperatures as low as 10 K in a cryogenic calibration facility at the Air Force Arnold Engineering Development Center (AEDC), TN.[6] After installation in the SPIRIT III telescope, the CQCM was a valuable tool for monitoring the mirror status during cryogenic testing of SPIRIT III at Utah State University Space Dynamics Laboratory (USU/SDL), thermo-vacuum testing at the NASA Goddard Space Flight Center (GSFC), and pre-flight measurements at the launch site. The sensitivity of the CQCM to mass deposition (for 10-MHz crystals) is given by

$$\Delta m/A(\mathrm{gm/cm^2}) = 4.42\times 10^{-9}(\mathrm{gm/cm^2}\bullet \mathrm{Hz})\Delta F(\mathrm{Hz}) \quad (1)$$

where

Δm = condensed mass, gm,
ΔF = change in CQCM frequency, Hz, and
A = active crystal surface area = 0.317 cm^2.

The contaminant film thickness, t, can be calculated if the film density is known. Typically, the film density is unknown, but it is usually assumed to be 1.0 gm/cm^3 to facilitate film thickness calculations. For unity density, the film thickness in Å is given by

$$\begin{aligned} t(\text{Å}) &= 0.442(\text{Å}/\mathrm{Hz})\Delta F(\mathrm{Hz}) \\ &= 0.442\ \text{Å for a frequency change of 1 Hz.} \end{aligned} \quad (2)$$

Temperature controlled quartz crystal microbalances

The TQCMs[7] were also built by QCM Research and were designed to operate at temperatures as low as –70°C and as high as 70°C. Preflight calibration and operational characteristics of the TQCMs were determined in ground testing.[8] The temperatures are controlled by a Peltier cooler/heater unit which is built into these Mark 10 TQCM units. The crystals oscillate at a frequency of 15 MHz. The mass sensitivity for the TQCMs is given by[7]

$$\Delta m/A(\mathrm{gm/cm^2}) = 1.96\times 10^{-9}(\mathrm{gm/cm^2}\bullet \mathrm{Hz})\Delta F\mathrm{Hz} \quad (3)$$

Using similar expressions to those derived for the CQCM results in the frequency vs thickness relationship (where again the density is assumed to be 1.0 g/cm^3),

$$\begin{aligned} t(\text{Å}) &= 0.196(\text{Å}/\mathrm{Hz})\Delta F(\mathrm{Hz}) \\ &= 0.196\ \text{Å for a frequency change of 1 Hz.} \end{aligned} \quad (4)$$

The TQCMs were mounted on individual radiators isolated from the main frame of the spacecraft to allow better thermal control. The heat generated by each Peltier thermoelectric device was radiated to space by the radiators. TQCMs 2-4 maintained an operating temperature of –50°C, whereas TQCM #1 operated at a slightly warmer temperature, –43°C, due to being mounted on a smaller radiator. As the satellite was rotated to achieve a commanded attitude, the projected area of the solar panel within theTQCMs' fields of view (FOVs) varied. In addition to the solar panel, the TQCM 1 field of view included some of the spacecraft electronics module, which is to the left of the +Z solar panels in Fig. 1. Furthermore, thermal blanketing of a UVISI box intrudes into TQCM 1's FOV. The degree to which the TQCMs can receive line-of-sight outgassed molecules from these surfaces has been calculated from spacecraft drawings.[9] The planned TQCM operational temperature range of –40° to –50°C was calculated to be cooler than all external contamination sources, such as the multilayer insulation, electronic boxes, and other non-cryogenically cooled surfaces of the spacecraft, and should be cold enough to condense many silicones and hydrocarbons outgassing from MSX materials.

The satellite axes are indicated in Fig. 1. Thus, TQCM 1 was pointed with components in the (–X,Y,Z) directions, TQCM 2 was pointed in the +Z direction, TQCM 3 had (Y,–Z) components, and TQCM 4 had (X,–Y,Z) components. The TQCM covers limited their fields of view (FOV) to a right cone with approximately 64-deg half angle. TQCMs 1 and 2 both had view factors which contained considerable area of the solar panels. TQCM #3 was positioned to look in a direction where minimal contamination would be seen. TQCM #4 was mounted on the +X face of the spacecraft and thus provided the deposition rate on the surfaces where all of the science instruments were located. The +X face of the spacecraft was predicted to cool to temperatures on the order of –20°C. Therefore, the deposition levels measured by the TQCMs at –50°C represent a "worst case" condition for the UV-visible instruments of UVISI and SBV.

Satellite Time Periods

The times after launch were designated as various time periods. They were as follows:

Pre-Cryo — The first 7 days in space which began at the time of launch and ended with the SPIRIT 3 cover release.

Cryo — Approximately 10 months duration which began when the SPIRIT 3 cover was released and ended when the focal plane array temperature reached ~ 13 K, signifying the depletion of the solid hydrogen cryogen.

Post-Cryo — Began at the end of the Cryo period and is still continuing –all of the cryogen has now been depleted and no data is being generated by SPIRIT 3. Data from UVISI, SBV, and the contamination instruments are still being collected.

SECOT (SPIRIT 3 End of Cryo Operations Test)

SECOT 1 — Fourteen 25-min pulses of solar heating on SPIRIT 3 telescope interior baffles to warm them above 160 K to remove any water film deposited on them. See Fig. 5 for MSX surfaces irradiated by the sun.

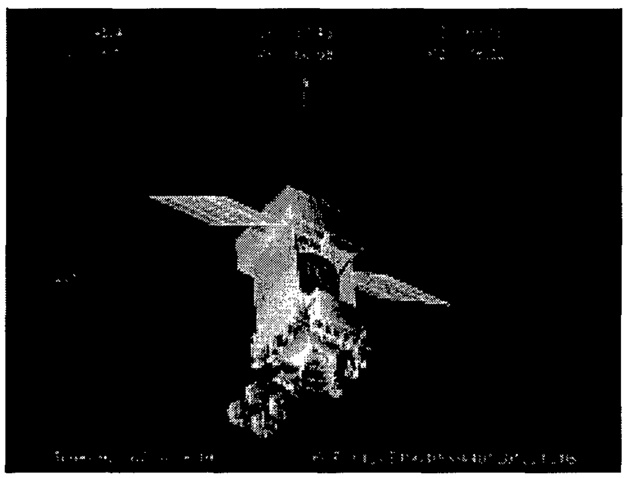

Fig. 5. Modeled view of MSX during baffle warming in SECOT experiments (as seen from the sun).

SECOT 2 — Sixteen additional 25-min pulses of solar heating on SPIRIT 3 baffles to warm all of the remaining interior SPIRIT 3 surfaces to above 160 K to remove any remaining condensed water inside the telescope.

Results

Results -- MSX Cryogenic Quartz Crystal Microbalance

The changes in CQCM frequency and temperature with time are shown in Figs. 6-7, respectively, for the time period from launch (Day 115, April 24, 1996) until Day 235 (August 23, 1997). This timeframe includes the time from launch through the end of the Cryo period and through the two SECOT experiments. The CQCM frequency-to-thickness conversion constant is 2.26 Hz/Å for an assumed film density of 1 gm/cc. At launch time, the CQCM frequency was approximately 2,492 Hz which was 12 Hz (~ 5 Å) higher than the frequency for the completely clean CQCM – 2480 Hz. During the first 7 days in orbit and prior to the SPIRIT 3 cover opening, the CQCM sensing crystal temperature dropped from an initial value of 28 K down to 21 K. During these 7 days, there was a gradual buildup of contaminant film on the CQCM, even though the cryogenically cooled SPIRIT 3 protective cover was still in place. Thermogravimetric analyses (TGAs) of the CQCM contaminants provided a means for determining the species and amount of contaminant condensed during this time. From two TGAs performed during the first 7 days on orbit

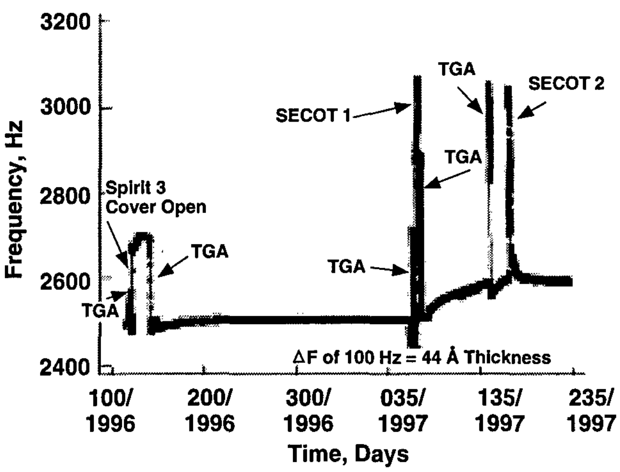

Fig. 6. CQCM frequency versus time since launch.

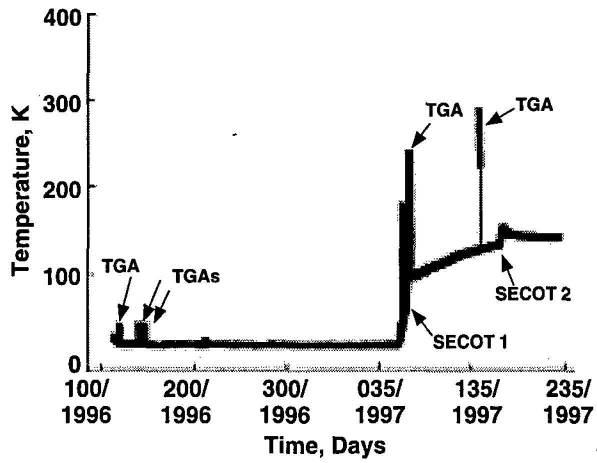

Fig. 7. CQCM temperature versus time since launch.

and prior to the cover release, it was determined that the contaminant deposited inside was primarily oxygen[1] which was caused by redistribution of previously condensed gaseous oxygen on the baffle within the telescope.

When the SPIRIT 3 cover was released on Day 122, 7 days after launch, there was a rise in CQCM frequency of about 163 Hz (72 Å) most of which occurred within 1 minute after cover release. Nineteen days after the cover release, another TGA was performed to determine the mass and species of the 72-Å-thick film. The results of this TGA can be found in Ref. 1. Most of the condensate evaporated between 28-30 K and was determined to be argon which came from the solid argon used as the cover coolant. This evaporation temperature is consistent with that seen from the argon vapor pressure vs. temperature curve. A small amount of deposit evaporated between 30 and 32 K and is believed to be oxygen which was deposited by redistribution prior to the cover release. The maximum evaporation rates were modeled using vapor pressure curves by treating the CQCM cryofilm at a pressure in equilibrium with the CQCM temperature. The results were a good fit for the two expected species argon and oxygen.

It is seen in Fig. 6 that very little film accumulation occurred after the cover release. Most of the small incremental increases occurred when the spacecraft was maneuvered into positions in which radiation from the Earth irradiated portions of the telescope baffles. The baffle surfaces after warm-

up caused some of the previously adsorbed gases on the baffle to be redistributed within the telescope. Since the last TGA was performed on Day 149, 1996, there was a CQCM frequency change of only 30 Hz (13 Å) for the remainder of the Cryo period. The total deposition on the CQCM, and presumably the primary mirror, was 155 Å and covered the time from the telescope cooldown prior to launch until the SPIRIT 3 end of life.

The TGAs indicated that the condensed cryofilm on the primary mirror was composed of argon and oxygen (see Ref. 1), neither of which absorb in the infrared, and hence had no effect on mirror reflectance. Even if it were assumed that the condensed species were either H_2O, C_2O, or CO (the infrared absorbing species most likely to be present), the change in mirror reflectance would be negligible.[1] Therefore, the film thickness of 155 Å had a negligible effect on MSX mirror reflectance and BRDF.

During the MSX Cryo period, it was determined that the performance of the SPIRIT 3 primary mirror had degraded significantly. On-orbit calibration data indicated an increase in primary mirror BRDF of about two orders of magnitude. The cause for this decrease has still not been determined. From the mass of contaminant measured by the CQCM and the laboratory BRDF results shown previously for argon films,[1] it was apparent that the argon film deposition could not have been the source of mirror degradation as the change in BRDF, even for a film 100 times thicker, was negligible.

At the end of the Cryo period, which occurred approximately February 27, 1997, the surfaces inside SPIRIT 3 began to warm up. One of the objectives of the Contamination Experiment was to determine how much, if any, H_2O had been deposited on the baffles near the entrance aperture. An experiment was planned in which the baffles would be warmed to a temperature of approximately 160 K to evaporate any H_2O that had condensed on the baffles. This experiment was accomplished by positioning the spacecraft at an attitude (Fig. 5) which allowed the solar flux to enter just inside the telescope baffle. Using 14 solar pulses of 25-min duration, the desired baffle temperatures were achieved. During this time the CQCM warmed from 51 K to 99 K, but remained cold enough to condense any H_2O that evaporated from the baffles and was incident on the CQCM. During the heating pulses the CQCM frequency increased approximately 450 Hz due to the deposition of H_2O. This corresponds to a film thickness of approximately 200 Å. At the conclusion of the heating pulses, another TGA was performed on the CQCM to determine the species of condensed mass. The results are shown in Fig. 8 where the film thickness vs. temperature is shown. The warm-up rate was 2.5 K/min. The film thickness, originally 200 Å, began decreasing at approximately 150 K and essentially all had been removed by ~ 165 K. This is a typical observation for H_2O films that are surrounded by vacuums on the order of 10^{-9} to 10^{-10} torr. The CQCM heating continued until a temperature of 240 K had been reached. It is also seen that essentially all of the deposited film was removed by the time the 165 K temperature was reached, indicating that the entire film was H_2O. The source of the H_2O was the multilayer insulation (MLI), which had some edges located near the entrance aperture. It is almost impossible to outgas the MLI, so this source of H_2O was not unexpected. It did show that the baffles were extremely efficient in eliminating the possibility of H_2O depositing on the primary mirror during the Cryo period.

Another TGA was performed on the CQCM near Day 140 (1997) in order to warm the CQCM

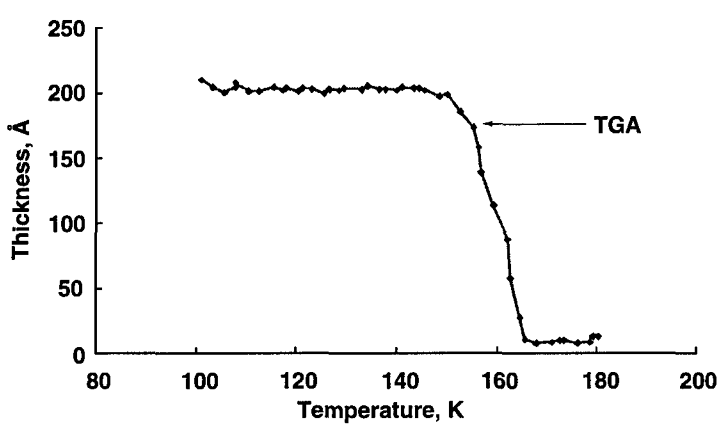

Fig. 8. Plot of CQCM film thickness versus temperature TGA performed after accretion during SECOT 1 solar heating experiment.

up to near 300 K. This was done to complete the CQCM frequency vs. temperature calibration curve for the additional temperature range prior to the beginning of SECOT 2. Between the times of SECOT 1 and SECOT 2 it is seen in Fig. 4 that the temperature of the CQCM (and SPIRIT 3) continued to increase. At the beginning of SECOT 2 on Day 167, the CQCM temperature had risen to about 140 K, nearing the borderline temperature where H_2O will condense/evaporate. During the second set of heating pulses, it is shown in Fig. 7, that the CQCM temperature increased from 140 K up to ~ 160 K. During this time the CQCM frequency increased from about 2600 Hz up to 3060 Hz—which was slightly higher than the deposition seen during the first series of heating pulses. This time, no additional heating was required from within the CQCM as the mass first increased and then slowly came back off as the CQCM temperature passed through the evaporation temperature region. By Day 175 essentially all of the previously condensed film had been removed.

Results - MSX Temperature Controlled Quartz Crystal Microbalances

The frequency vs. time plots are shown in Figs. 9 - 12 for TQCMs 1- 4. Only one temperature vs. time plot is shown (Fig. 13) since three of the TQCMs all had essentially the same temperature history. The temperature of TQCM #1 varied between −40°C and −43°C because it had a smaller radiator than the others. The time periods for Figs. 9-12 are the same as those previously shown for the CQCM. The TQCMs had the disadvantage of being sensitive to incident solar flux. Negative shifts in frequencies (ΔF) from 300-450 Hz were seen for the TQCMs when the spacecraft orientation went from no sun to full sun. In the satellite park mode only TQCM 4 saw full sun. According to the QCM Research personnel, this frequency decrease with solar radiation is caused by the thermal stress generated in the quartz crystal by the solar exposure.

The many spikes in the data of Figs. 9-12 are indicative of times when the spacecraft was maneuvered out of park mode to other attitudes that caused direct solar irradiance on the TQCMs. These solar effects complicated the data analysis

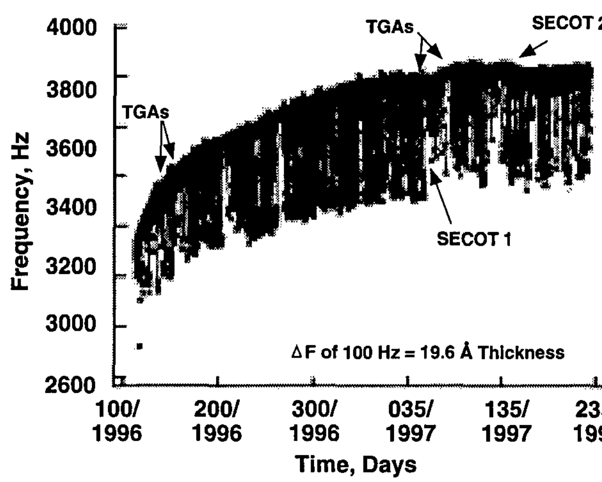

Fig. 10. TQCM #2 plot showing increase in frequency due to accreted mass at (+Z) location.

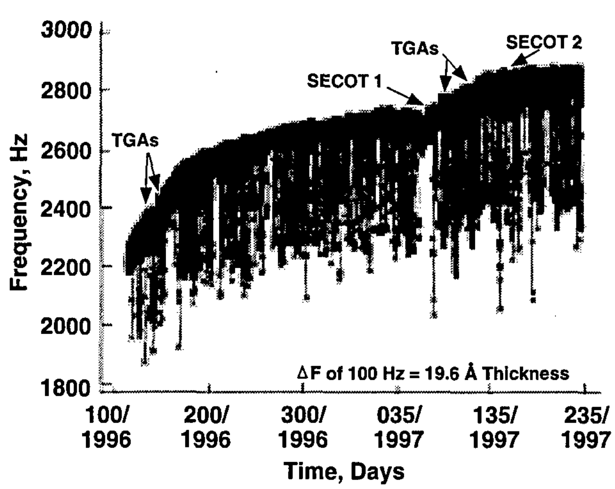

Fig. 9. TQCM #1 plot showing increase in frequency due to accreted mass at (+Y, +Z) location.

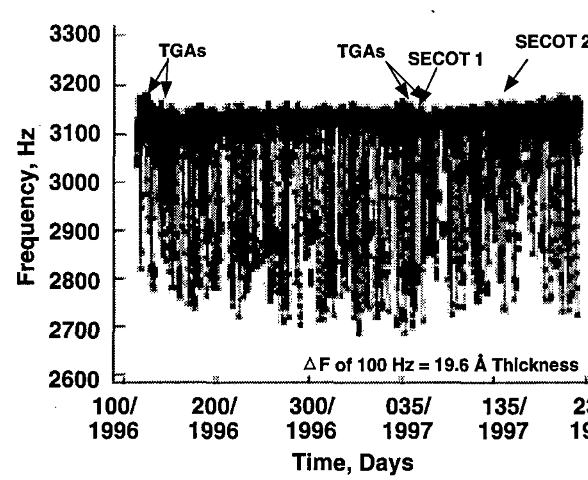

Fig. 11. TQCM #3 plot showing increase in frequency due to accreted mass at (+Y, −Z) location.

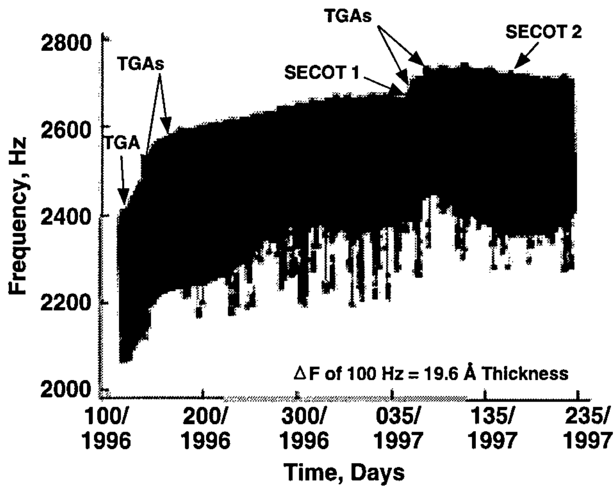

Fig. 12. TQCM #4 plot showing increase in frequency due to accreted mass at (+X) location.

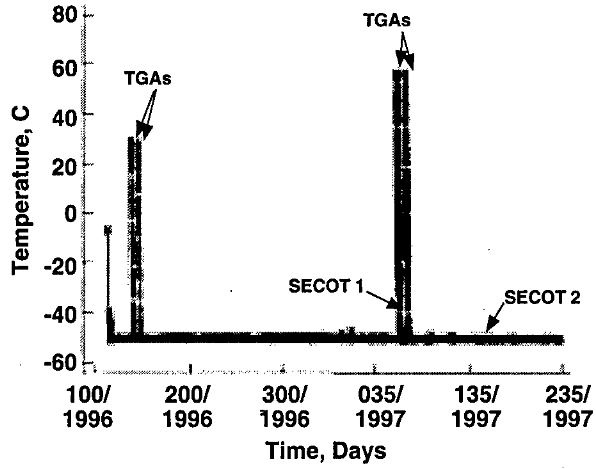

Fig. 13. Temperature versus time for TQCMs 2-4 since launch.

on a short-term basis, but the data corresponding to TQCM darkness times can be used to determine the long-term deposition thickness and rates. Using the data points at the top of the curves, which correspond to times when the TQCMs were in darkness, a thickness trend was developed (see Ref. 1). Since launch, total contaminant deposition measured by TQCMs 1 - 4 is 134, 144, 13, and 63 Å, respectively. This deposition has occurred during the first 486 days in space. TQCMs 1 and 2 both have view factors of the solar panels, which apparently are the predominant sources of contaminants on MSX. The rate of deposition has varied considerably during the 16 months in orbit. The deposition rate on the TQCMs increased after the SPIRIT 3 telescope and dewar warmed up at the end of the Cryo period. TQCM 3, as expected, has shown the least amount of deposition since it has very little in its field of view.

In contrast to TGA data observed for the CQCM, the TQCM TGAs data sets were of minimal value due to the "solarizing" of the contaminants on the external sensing crystals. This feature has been seen previously in laboratory measurements as well as in previously flown QCMs in space where the outer crystal is exposed to the sun's UV wavelengths. TGAs on each of the four TQCMs showed very little if any change in frequency due to the crystal warm-up to 60°C. The contaminant, presumably comprised of organics and silicones from material outgassing, was essentially "baked on." The times that TGAs were performed are noted in Fig. 13. The TGAs were performed in pairs in order to get a frequency vs. temperature plot for each TQCM while contaminated, followed by another with the supposedly cleaned crystal. However, the TGAs were unsuccessful in reducing any appreciable mass from the contaminated surface. The first set of TGAs was performed between days 140-150 (1996) and the temperature increased from –50°C to +30°C. The second set was performed between days 55 and 75 (1997), and the temperature increased from –50°C to +60°C. Each set of TGA data required the use of the tape recorder and this sometimes reduced the time available due to higher priority experiments. As seen in Fig. 13, the TQCM Peltier heating/cooling units have been very dependable in maintaining the commanded temperatures over the entire mission.

Flight data uncertainty

The QCM mass calibration expressions were obtained from the vendor, QCM Research. These values of 4.42×10^{-9}(gm/cm^2 • Hz) for the CQCM and 1.96×10^{-9}(gm/cm^2 • Hz) are estimated to be accurate within $\pm$1 percent based on earlier experiments in which density values for condensed gases were obtained. The CQCM frequencies were stable within $\pm$1 Hz when operated at 20 K. At ~ 150 K, the uncertainty in frequency increased to a value of $\pm$2 Hz. The temperatures had a variation of $\pm$0.25 K. The TQCM stability was strongly affected by incident solar flux and other thermal conditions. At a given thermal condition the uncer-

tainty in frequency was ±2 Hz. Based on the laboratory operation of some of these and similar units,[8] a stable thermal condition may still result in a TQCM frequency variability (noise level) as large as ~ 4 Hz. As discussed previously, the solar effect on the TQCM frequency was considerable, with the result being that only values taken during local TQCM darkness could be used for characterizing true contaminant deposition.

Summary and Conclusions

The Midcourse Space Experiment (MSX) satellite QCMs have proven to be quite useful for monitoring the on-orbit contaminant mass buildup on the SPIRIT 3 cryogenic telescope primary mirror and on the satellite external surfaces. After ~10 months in orbit, the CQCM (and primary mirror) accumulated 155 Å of condensate on the 20 K surfaces. Almost 50 percent of this condensate was due to the argon condensed during the SPIRIT 3 cover release. Essentially all of the condensate during the Cryo period was argon and oxygen. There was no indication of any water or carbon dioxide deposited which was determined from the thermogravimetric analyses data obtained before and after the cover release. Ground tests on the optical effects of condensed films on cryogenic mirrors at 20 K indicate that this 155 Å film had negligible effect on the mirror scatter and reflectance.

The four TQCMs mounted on satellite external surfaces were operated at temperatures of – 40°C - 50°C (depending on location) and have shown accumulations between 13 and 144 Å, depending on the TQCM view factors on the spacecraft. The TQCMs having the solar panels in their field of view (TQCMs #1 and #2) have shown the largest deposition rates. The solar radiation incident on the crystals have shown two separate effects: (1) a quick response negative shift in output frequency between 300 and 400 Hz when solar radiation is incident normal to the crystal, and (2) the solar UV component solarizes the contaminant such that during TGAs, only a small portion, if any, of the condensed mass is evaporated. The TQCMs are continuing to accumulate mass, and the long term trends established for MSX will be extremely valuable for future satellite systems.

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